Study on incorrect predictions for simulations of the vacuum infusion process

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Abstract

The vacuum infusion process is a Liquid Composite Manufacturing (LCM) process in which the preformed reinforcing fibres are impregnated with the fluid matrix using the pressure difference produced by the evacuation of the mould cavity. In order to speed up the infiltration process, it is common to use a highly permeable flow distribution medium on top of the preform. On doing so, thw matrix infiltrates the preform predominantly through the thickness direction of the part. Filling simulations of such vacuum infusion processes having layers with vastly different permeabilities, when done with software tools that make use of the Finite Volume Method (FVM) typically show an incomplete filling of the bottommost layer of cells, which is in contrast to what is observed experimentally. This work aims to study this error and propose solutions for rectifying this error.

Introduction

Composite manufacturing processes in which liquid matrix is forced into a dry preform of the reinforcing material with the help of a pressure difference are generally grouped under Liquid Composite Manufacturing (LCM) processes. The vacuum infusion process and it’s many variations are a group of LCM processes that are popular because their relatively low cost in comparison to other composite manufacturing processes. In the vacuum infusion process, a one-sided mould is used, with a flexible membrane on the other side. The reinforcing preform is placed on the one-sided mould, covered with air-tight vacuum bagging with inlets and outlets for the fluid matrix, and

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*Corresponding author: christof.obertscheider@fhwn.ac.at then evacuated and compacted by applying a vacuum to the mould. The compaction pressure is provided by atmospheric pressure acting down on the vacuum bag. The fluid injection pressure is the sum of pressure due to the weight of the fluid column in the fluid container, and the pressure acting down on the free surface of the fluid (usually atmospheric pressure).

It is important to ensure that the preform is fully impregnated with the matrix. Any dry spots, air bubbles or matrix rich zones can lead to improper transfer of loads between the matrix and the reinforcing fibres, leading to a reduction in load bearing capacity of the part. For this reason, the design of the mould and the placement of the inlets and outlets are very important for LCM processes. Filling simulations can help in predicting the propagation of the fluid flow front inside the mould and can be used in the design of the moulds. The two popular approaches employed for filling simulations are to use Darcy’s law for flow through porous media, or to use a modified version of the Navier-Stokes equations. Most purpose-built simulation tools such as PAM-RTM and RTM-Worx make use of Darcy’s law, while general purpose CFD software such as ANSYS FLUENT, Simulia Abaqus/CFD, Comsol Multiphysics and OpenFOAM make use of the Navier-Stokes Equations solved using the Finite Volume Method (FVM) or the Finite Element Method (FEM).

This work details an error in the flow front propagation predictions of the vacuum infusion process when using simulation tools that are based on FVM.

Description of the Error

A common modification of the vacuum infusion process is to place a high permeability flow distribution medium over the reinforcing fibres with a porous peel ply placed in between. The matrix will flow much faster through the flow distribution, with the flow in the preform being predominantly because of matrix seeping down from the flow distribution medium. This results in a faster impregnation of the preform in comparison to when no flow distribution medium is used. If a rectilinear flow case is considered, it can be observed that the flow front in the preform layer lags behind the flow in the flow distribution medium (or it can be considered that the flow in the flow distribution medium leads the flow in the preform). The relation of these two flow fronts will henceforth be termed as „lead-lag“.

In simulations of the vacuum-infusion process, it can be observed that bottom-most layer of cells are not completely filled by the matrix, which is in contrast to what is observed experimentally [1]. This results in an error in the predicted flow front in the preform, which is termed the „lead-lag error“.

In order to demonstrate this error, simulations of the vacuum infusion process for a rectilinear flow case are performed with both OpenFOAM and ANSYS FLUENT. The geometry for the simulations consists of a relatively higher permeability region representing the flow distribution medium on top of a lower permeability region representing the reinforcing preform. The geometry together with the chosen dimensions is shown in Figure 1. The error is most apparent when fluid injection occurs only through the flow distribution medium. The boundary conditions for the simulations are shown in Figure 2. Simulations are performed using typical values for the permeabilities of the flow distribution medium (1e-9m²) and the reinforcement preforms in the flow direction (2e-12m²) and thickness direction (2e-13 m²) [2][3]. The material properties of a typical plant oil are used for the matrix, with the properties of air being used for empty cells (since there is never a perfect vacuum). In order to observe the filling behaviour in the cells, the fluid volume fraction of the matrix (a quantity for which the value 1 corresponds to a cell that is completely filled with the matrix and the value 0 represents a cell that is completely devoid of matrix) is plotted. The volume fraction plots obtained from OpenFOAM and ANSYS FLUENT are shown in Figures Figure 3 and Figure 4 and clearly demonstrate the lead-lag error.

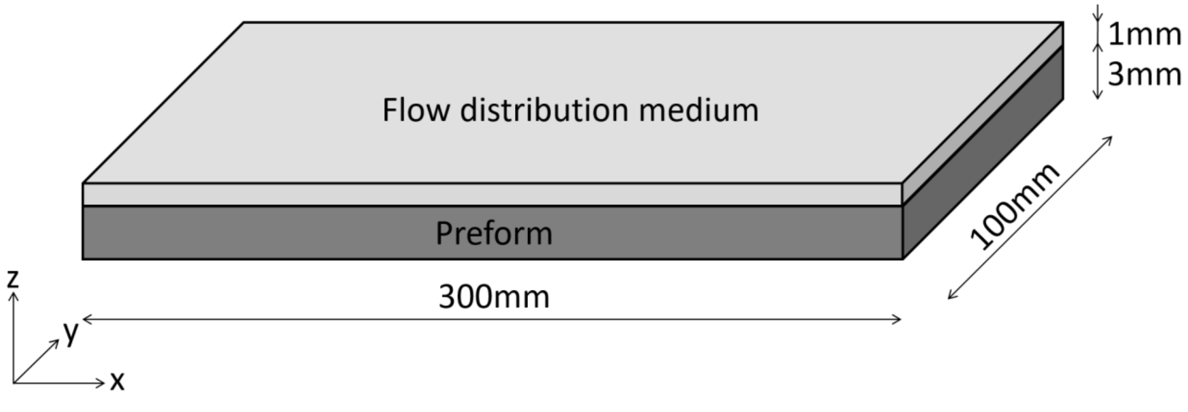

Figure 1: Model geometry

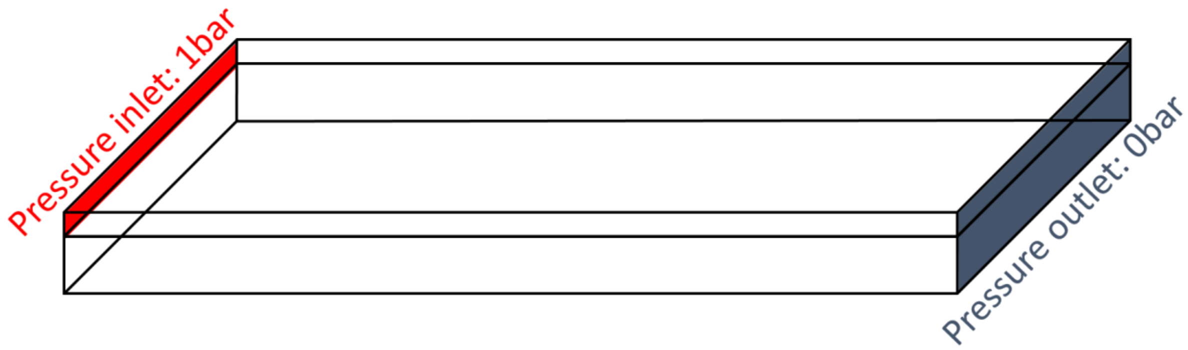

Figure 2: Boundary conditions

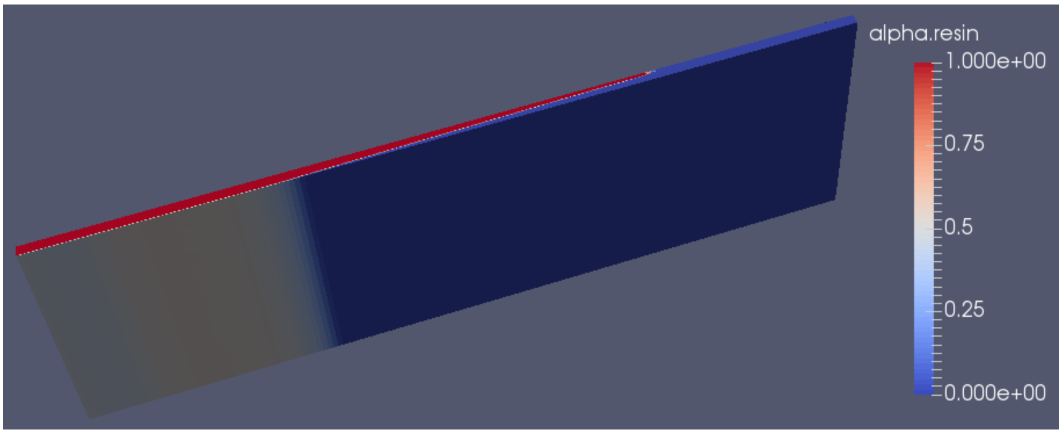

Figure 3: Volume fraction plot for matrix in OpenFOAM

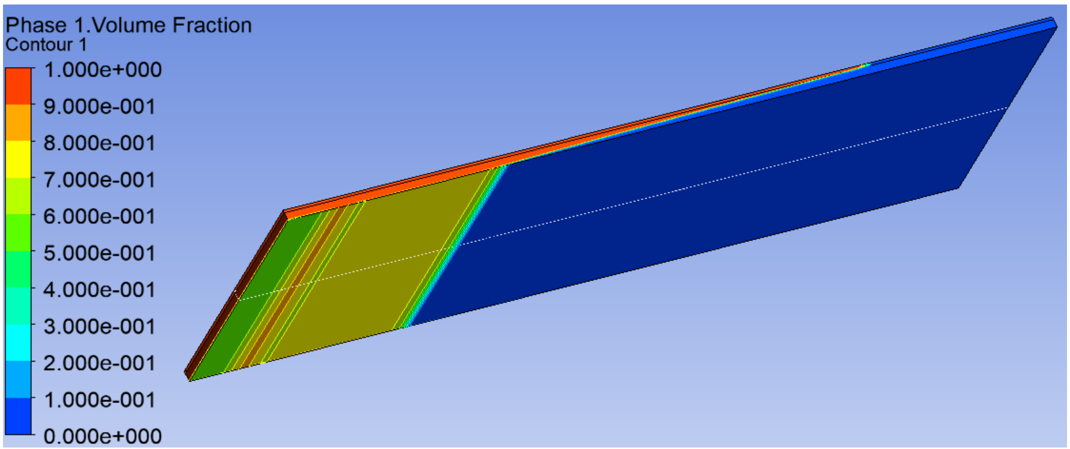

Figure 4: Volume fraction plot for matrix in ANSYS FLUENT

Description of OpenFOAM Solver

OpenFOAM was chosen for studying and testing potential solutions for solving the lead-lag error because the source code is available under the GNU General Public Licence (GPL). For studying the lead-lag error, a custom OpenFOAM solver was made by combining two standard OpenFOAM solvers – interFoam and porousSimpleFoam, with interFoam being the base solver. interFoam is a multiphase solver for two incompressible immiscible fluids [4]. porousSimpleFoam is a solver for turbulent flow through porous media. By copying the relevant parts from the porousSimpleFoam solver with modifications wherever necessary, support for modelling flows through porous media is added to the base solver. The custom solver was validated by a comparison of simulation results with predictions from Darcy's law [1][5][6].

Results

In order to better understand the lead-lag error, virtual probes are used in the bottommost 4 cells as shown in Figure 5 to track the development of pressure, velocity and the fluid volume fraction ($alpha$) over the course of the simulation in these cells. The probe results for vertical and horizontal velocity, fluid volume fraction and pressure are shown in Figure 6.

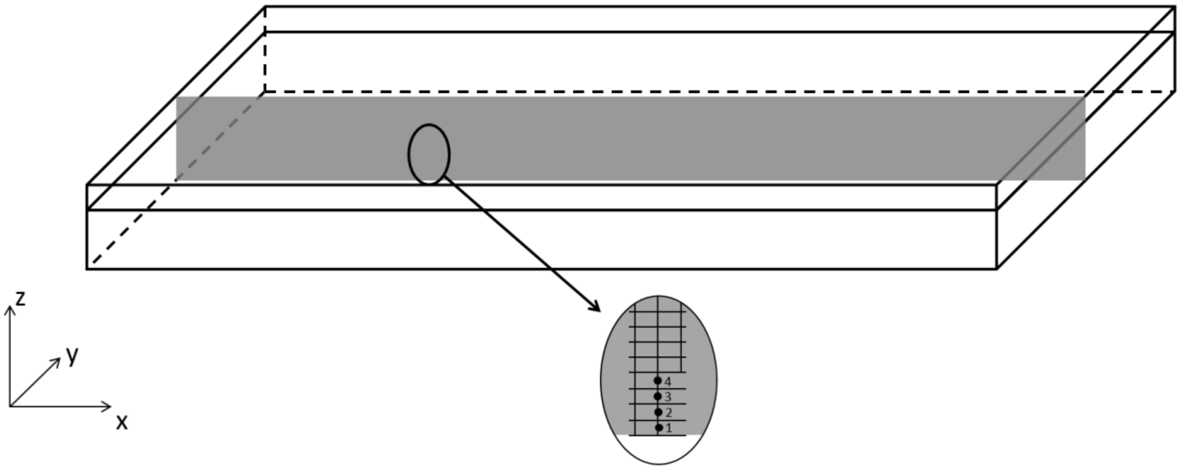

Figure 5: Position of the probes

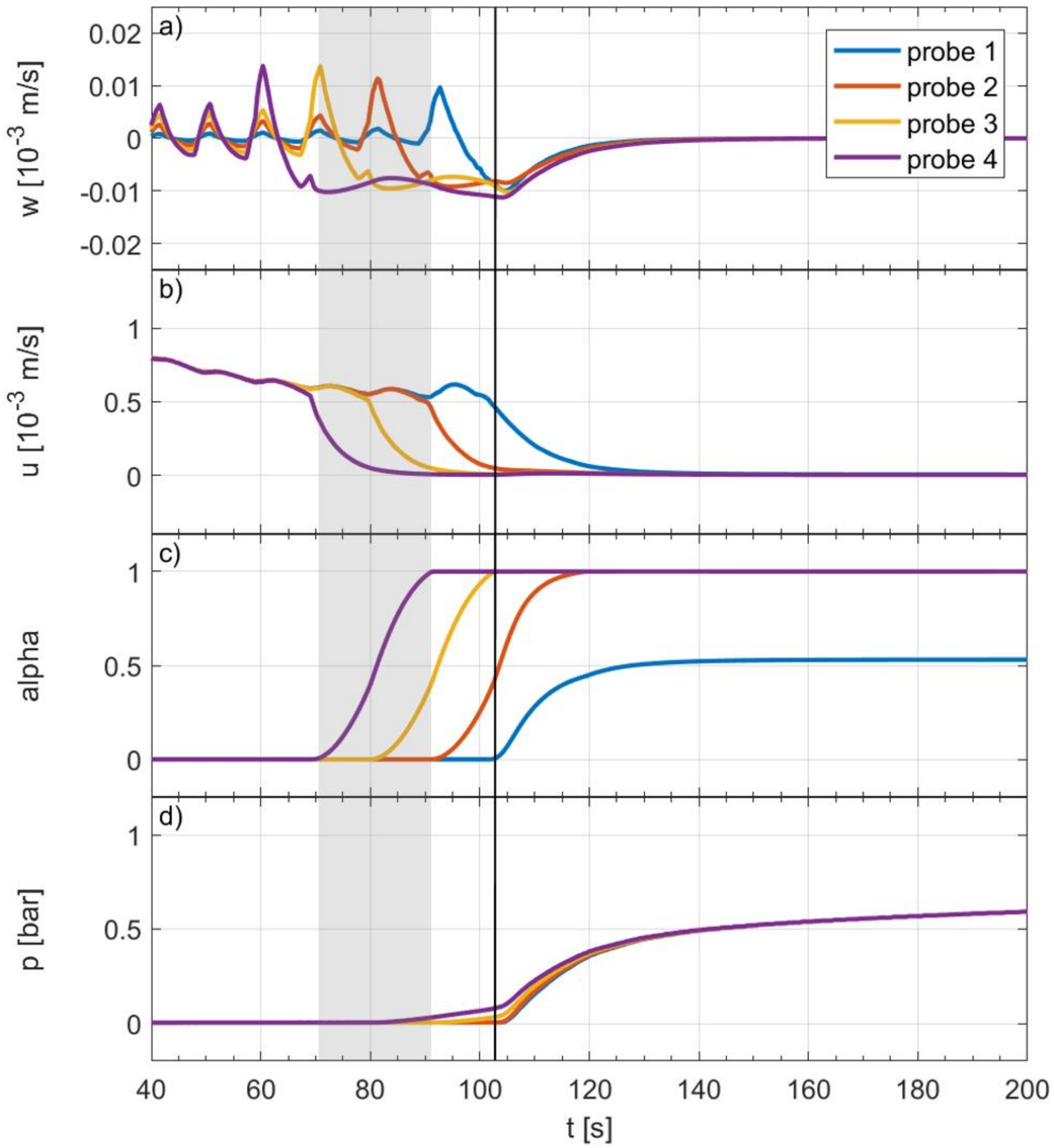

Figure 6: Probe results for vertical and horizontal velocity (w and u), fluid volume fraction ($alpha$) and pressure (p)

Discussion

From Figure 6, it can be observed that that the vertical velocity w from probe 4 remains fairly constant during the filling of cell 4 (shown by the shaded portion of the figure), while the horizontal velocity u decreases to zero by the time the filling of cell 3 begins. From this, it can be deduced that cell 4 is filled in the vertical direction, with the air in the cell initially being transported horizontally to the right and then vertically downwards. The cells 3 and 2 are filled in the same as cell 1. The filling of cell 1 stops after the first half of the process since vertical transport through the wall is not possible. This is because of the lack of a sufficient pressure difference between cells 2 and 1. From Figure 6, it can be seen that while there is a significant pressure difference between the cells 4 and 3, and between cells 3 and 2, the pressure is nearly the same in cells 2 and 1 (the pressure plots for probes 2 and 1 almost coincide with each other). This pressure increase causes the velocity of flow in the downward direction in cell 1 to decrease to 0, leaving the cell only partially filled.

Proposed Solutions

The following solutions are proposed for resolving the lead-lag error:

1. Treating air as a compressible fluid.
2. Modifying the balance equation which determines the fluid volume fraction.

It is planned to attempt to resolve the lead-lag error by modifying the custom OpenFOAM solver used in this paper by implementing one of or both of the proposed solutions and calibrating the results by comparing the simulation results with experimental observations. This will be covered in future works.

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